## Project Title

Due Date:

Name:

Course:

Instructor:

**Abstract**

This report involves simulating a four loop Pressurized Water Reactor (PWR) using a numerical loop momentum balancing approach. The first section details the theoretical basis for the pressurized water reactor and how the momentum balancing equations provide an accurate approximation for the reactor physics. Next, the report dives into the specific methods used in order to discretize the momentum balance equations for the specific four loop PWR before determining the appropriate Reactor Coolant Pump (RCP) and Steam Generator design parameters needed to meet required mass flux and core inlet temperature rises. This reactor is then analyzed for performance in three pump transients. The first transient evaluates performance in a loss of all AC casualty where all RCPs trip off simultaneously. The second evaluates a locked rotor casualty impacting a single loop, where the loop effectively loses all flow. The third transient analyzes a single RCP shear inducing reverse flow through the associated loop. Finally, the number of clogged steam generator tubes are adjusted to determine the proportion required to reduce mass flow rates by 10% of steady state.

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# Introduction and Theory

This report analyses many reactor safety considerations which are involved in designing a pressurized water reactor (PWR). PWRs are common in the nuclear power industry, so analyzing this design provides insight into limiting casualties, reactor safety concerns, and the importance of proper reactor plant design. The specific geometry analyzed in this report involves a four loop PWR, where each loop has a Reactor Coolant Pump (RCP), a steam generator, and no check valves to prevent backwards flow. Loop one is used to determine the transient behavior, and the other three loops are grouped into a set of symmetric loops collectively referred to as loop two. A visual depiction of the PWR is seen in the figure below:

A diagram of a building

Description automatically generated

Figure : Visualization of PWR Nodes

Where the node categorization is given by the following table:

A table with text and numbers

Description automatically generated

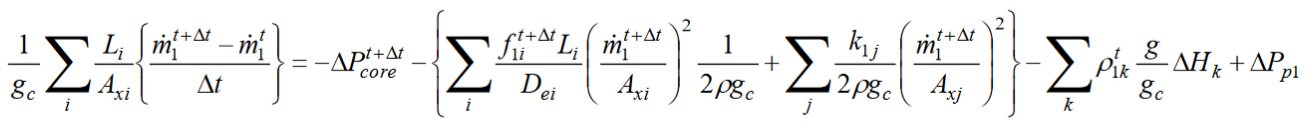
Before discussing the results of the transients performed as part of this report, it is important to understand the theory used to numerically model the PWR. Fundamentally, this report calculates the mass flow rate by ensuring momentum is conserved within the reactor. As the heat transfer from both the steam generator and fuel rods depend on the mass flow rate, the flow rate is used to determine the current fluid internal energy and temperatures in the PWR loops and core. While these equations are continuous, this report discretizes the momentum and internal energy at each node shown in Figure 1, which assumes homogenous properties in each node. This report sizes the RCPs and Steam Generators to meet minimum required mass flow rates and core inlet temperatures. Afterward, it analyzes the impact of various transients important for reactor safety on overall reactor performance. The first transient evaluates performance in a loss of all AC casualty where all RCPs trip off simultaneously. The second evaluates a locked rotor casualty impacting a single loop, where the loop effectively loses all flow. The third transient analyzes a single RCP shear inducing reverse flow through the associated loop. The final transient analyzes the number of clogged steam generator tubes required to reduce mass flow rates by 10%.

Also includes project objectives.

Typically, the project report can be between 10 to 30 pages long. Grading will be focused on content, logic, and not the size of the report.

# Methods

As momentum is conserved within the reactor, any momentum going into a node must either exit the node or be stored within it. This report models the momentum in each node using the below equation:



In the above equation, m is the mass flow rate, L is the length of the node, A is the node’s cross-sectional area, D is the node’s equivalent diameter, k is the minor friction losses, f is the Colebrook friction factor, ρ is the water density, and ∆H is the change in height over the node. As the timestep advances, this momentum balance equation is solved for the node’s mass flow rate at time t+∆t. As the mass flow rate in each node changes to conserve momentum, the internal energy and corresponding bulk fluid temperature will also change. This behavior is modeled by determining the new equilibrium internal energy at each node with the new equilibrium mass flow rates through the below equation:

A math equations and formulas

Description automatically generated with medium confidence

Here, V is the node volume, q is the heat flux into the fluid from the node (positive for heat flowing into the fluid), and u is the node’s internal energy.

There are several methods which can be used to solve the momentum and internal energy equation. In developing the numerical simulation two different methods were investigated – a Newton Raphson solver and a direct iterative solver. The Newton Raphson solver takes in a matrix of equations, determines the associated jacobian matrix, and then solves for new minimum input values based on the derivatives calculated in the Jacobian. This method works best for equations that have limited numbers of local minima. The direct iterative solver updates individual inputs based on information from the previously calculated inputs. This process repeats until the individual inputs converge on the steady state values.

The following matrix must be solved to balance the overall momentum balance for the PWR:

A number and a number of numbers

Description automatically generated with medium confidence

An iterative approach can directly solve for the input mass flow rates, as a1, a2, ac, b1, b2, bc, and n are all determined by known node parameters at each time step. For each time step, the project simulates a time dT by directly solving this matrix to update the new mass flow rates.

This equation provides the updated mass flow rates for each loop and the core. These are then input into an iterative solver developed to solve the internal energy equation. As the implementation of the Newton Raphson was not well behaved, an iterative solver was developed to solve the internal energy equation. The above momentum equation can be rearranged to see:

ITERATIVE MOMENTUM HERE

This loop is ran for each node until the internal energies in the node no longer update.

In order to determine the maximum surface temperature of the cladding, one dimensional PCT equations were solved based on the current heat flux from the corresponding core node. INSERT PCT EQUATION HERE

As the assignment required maintaining the maximum surface temperature of the fuel cladding below saturation temperature, only convective heat transfer from single phase flow conditions is analyzed. Based on the heat transfer coefficient between the bulk fluid and the fuel rod, the temperature rise at the surface of the cladding is determined.

Review the methods and the code used for the project

# Problem Formulation

Problem A

Sizing the reactor coolant pumps

Problem B

Determining the required pump flywheel inertia rates to remain below Tsat

Problem C

Tripping off one pump

Problem D

Locked rotor condition

Problem E

Reverse flow condition

Problem F

Minimum SG tubes required to reduce flow rates by 10%

For example, include schematic of the domain, what is being done and how the results are obtained.

# Results and Discussion

Problem a

Problem b

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Problem c

A graph of a function

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Problem d

A graph of a diagram

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Problem e

This transient was unable to be fully modeled with the current state of the Python simulation. Even once the RCP pump shear occurred to allow reverse flow conditions, the calculated pressure drop across the core was still low enough that the flow preferred to travel up the reactor vessel as opposed to around the downcomer region associated with loop one. This clearly illustrates an error in the implementation of the momentum balancing and internal energy discussion. While the mass flow rate does not appropriately update to reflect the reverse flow through loop one, the rest of the PWR behaves similar to problem c, where there is an initial decrease in flow through the impacted loop. However, this transient sees the mass flow rate increase by a greater proportion after the scram, most likely as a result of the exit loss coefficient of the pump.

A graph of a line

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Problem f

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863 clogged tubes

Includes the performed parametric studies and the analysis of the results. This section should include all the tests performed, results and its interpretation.

Specifically, this project requires several specific tasks (see description). Clearly separate the results and discussion for each task

# Conclusions

Discuss problems / issues / good results as well as potential future work. Future work should evaluate reactor safety in longer time domains in order to appropriately factor decay heat removal as a criteria for PWR casualty response.

# References